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EFFECTS OF TIRE INFLATION PRESSURE AND CTI ON ROAD LIFE AND VEHICLE STABILITY

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ABSTRACT

Central tire inflation (CTI) systems allow a vehicle operator to change the tire inflation pressure while the vehicle is moving. Lower tire inflation pressure has been found to reduce road wear and improve vehicle performance in areas of traction, braking, ride quality and vehicle maintenance.

The benefits of lower tire pressure on road systems have been reported in various publications and reports however, the influence of lower tire pressures (higher tire deflection) on the stability and control of heavy vehicles is not well understood.

This paper summarises the significant CTI research findings with respect to the infrastructure and explores the effects of CTI on vehicle stability and control performance. The analysis focused on a 9 axle B-train in the loaded state assuming GVW of 75,500 kg, and 69,000 kg; and in the empty state.

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CTI EFFECTS OF ON ROADS

In 1993, a comprehensive full-scale test was conducted by the US Army Corps of Engineers to determine the effects of CTI on road and tire life (1 and 2). Test loop roads were built under tightly controlled conditions ensuring a well defined sub grade, base course, and running surface. The loop roads were divided into sections of differing road types. The sections varied in construction from native materials to unpaved aggregate running surfaces with various base course thicknesses to high quality paved roads with various asphalt thickness. The roads had two travel lanes, one travelled by test vehicles with high tire inflation pressure and the other with vehicles having low tire inflation pressure. Failures or distress in high tire pressure lane were more pronounced than in the low-pressure lane. When failure occurred in both lanes, the ratio of low tire pressure to high tire pressure traffic to initial failure ranged from 1.5 to 21 (sic) for

unbound surfaces. There were no appreciable differences in the performance of aggregate surfaced horizontal curves due to the different tire pressures. The performance of the straight and flat aggregate sections were considerably better in the low tire pressure lane as compared to the high pressure lane.

More ravelling was observed in the low tire pressure lane in the horizontal curves of the asphaltic concrete sections than in the high tire pressure lane. Comparative pavement performance of the thicker asphaltic concrete roads is unavailable because traffic was stopped before failure occurred. This could imply that the beneficial effects of extending road life through the use of CTI may be less significant on strong roads.

A three year joint study (3) with Forest Engineering Research Institute of Canada (FERIC) and the Alberta Newsprint Company (ANC) investigated the potential for using a B-Train combination equipped with central tire inflation (CTI). Three road surfaces were studied; native earth block-entry, lightly gravelled forest access roads and asphaltic-concrete highways. The native earth thawing block-entry road was constructed as a 100m X 75m two lane oval track. The track had a low section, a level section and a 6% grade. The outer lane was used for "high" tire inflation pressure and the inner lane was used for "low" tire pressure conditions. The single test vehicle operated on one lane at high tire pressure until the road failed - defined as when ruts of 10 cm in depth occurred. It then travelled on the other lane at the low tire pressure setting until the surface failed. During the test program, the tire inflation pressure settings were as follows; high-pressure condition was set to 100 psi; low pressure ranged from 34 to 39 psi. The test vehicle was a 7-axle unit having a GVW's of 56.5 tonnes.

The tests found that tires inflated to the high pressure (normal) settings rutted the road surface approximately nine times faster than when inflated to the low pressure settings. This extreme result is due in part to the very weak structural condition of the road. It is estimated that the road had a CBR of 3, which is typical of weak, thawing conditions. In general, initial rut development decreased by 77% when low tire pressures were used.

Lightly gravelled roads were typical of forest access roads in Alberta. They were built with approximately 60 cm of native material and surfaced with 8 cm of crushed gravel. The tire pressure settings used during the test are shown in Table 1.

Table 1. Tire inflation pressures for gravelled road tests.

TEST CONDITIONS AND TIRE PRESSURES			
Tire Pressure Condition	Steer Axle (psi)	Drive Axles (psi)	Trailer Axles (psi)
Low	75	30	27
Moderate	75	55	60
High	95	90	85

From the tests, it was estimated that high inflation pressure increased rutting by a factor of two compared with moderate tire inflation pressure. Low tire inflation pressure settings were used on road previously rutted by high inflation pressure settings. The low inflation settings produced a "healing" effect on the road surface by reducing the existing ruts by approximately 10% resulting in a more uniform and compact running surface. This healing phenomenon does not occur in all cases and is diminished as tractive requirements increase. The study estimated that on lightly gravelled roads, low tire inflation pressure reduces rut development by up to 90%.

One possible explanation for the reduction in rutting associated with reduced tire inflation pressure is that vertical tire force distribution across the lateral plane of the contact patch varies

significantly with tire inflation pressure. Under high tire inflation conditions, the highest contact stress is located at the centre of the contact tire patch and the stress reduces towards the shoulder of the tire. This will have the effect of manipulating the unbound road material out of the wheel path. Under low tire inflation pressure, the stresses are highest at the shoulders of the tire and are reduced towards the centre tending to capture surface material of the road. This concept is illustrated in [figure 1](#).

A further study (4) showed that reducing tire pressure will reduce pavement strains and extend pavement life. This was found to be true for both fatigue and rutting failure. Pavement section stiffness is critical to determining whether to allow any heavy vehicles with or without reduced tire pressure or tire load or both. The study found the effect of reducing tire pressure to be larger on thinner pavement sections and larger for fatigue (tensile strain) than rutting failure (vertical compressive strain). Another study (5) found that a significant reduction in unpaved forest road damage occurred as tire sidewall deflection approached 20%. There was only a minor decrease in road damage as the tire sidewall deflection was increased to 30%.

TIRE WEAR, TRACTION AND RIDE EFFECTS

Tire Wear

Improvements in tire wear, ride quality and traction have all been attributed to reduced tire inflation pressure. A study (6) was conducted using the closed loop AASHTO-type circuit where road surfaces varied from pot holes to double penetration chip seal roads to type II asphalt concrete surfaces. Tests were conducted under two test conditions; high pressure (10-12% tire sidewall deflection) and low pressure (20-22% tire sidewall deflection). Over a distance of 3,600 km the reduction in tire wear attributed to reduced tire pressure was 15%. Traction was found to improve by 12-18%. A significant reduction in input road vibration to the driver was reported resulting in a more comfortable ride with less driver fatigue.

Following the formal test program, the tires were subjected to an additional 150 km of severe rock course. The results for 36 radial truck tires from the overall tire durability test are shown in Table 2.

Table 2. Tire durability results - number of occurrences.

Type Of Tire Damage	High Tire Pressure	Low Tire Pressure
Undercut flex cracks	540	303
Rib cracks	147	49
Rib cuts to belt	5	0
Tread cut chunk-outs	171	35

Tire temperature measurements were also taken. With tire loads of 2,050 kg, and 20% tire deflection, the temperature measured in the tire is shown in Table 3.

Table 3. Tire temperature with speed

Tire Load 2,050 kg	
Vehicle Speed (km/h)	Tire Temperature (deg C)
66	88
88	99
108	116

Another study (7), examined tire wear rates and tire carcass life. The study stressed that radial tires should be used because of the flexible sidewall design. It recommended that bias ply tires should not be used (the validity of this recommendation has been questioned by FERIC on the basis of historical experience with military applications). It was also reported that the US Tire and Rim Association sets tire pressures for load and speed for all tire manufactures conducting business in North America. Individual manufacturers can provide additional pressure reduction in accordance with their own criteria but only by permission of the manufacturer on a case by case basis. At the time (7) was written, the Forestry Service had obtained interim standards for reduced pressure operation from the US Tire and Rim Association. However since that time, the Tire and Rim Association has issued recommended pressures for the following six tire sizes at a vehicle speed of 35 mph:

- 11R22.5
- 11R24.5
- 12R22.5
- 12R24.5
- 295/75R22.5
- 315/80R22.5

The test program chose a tire deflection of 20% for low and moderate speeds and a tire deflection of 10% for high-speed operation. The tests were conducted at the Nevada Automotive Test Center, running over a designated test course with 12 different roadway sections including a severe rock course. The radial truck tires at reduced pressures experienced approximately 15% less tire wear than tires operated at the standard highway pressure. After the tires had finished running through their original life, they were holographed, inspected and then retreaded. The analysis revealed equivalent residual durability after running through its original life.

A second test revealed that there was no substantial difference in tire wear rate between CTI and non-CTI applications. The Goodyear Tire and Rubber Company had the following conclusions from its field evaluation.

- 1) Original tread wear was equivalent for tires which operated with and without CTI.
- 2) At the end of original tire life, CTI tires were acceptable for retreading.
- 3) Tread wear varies significantly from location to location, i.e., low, moderate, and fast tire wear rates; and
- 4) Because of many uncontrolled test variables, only tires run at the same location, using the same roads, can be directly compared.

The overall study concluded that there are no significant detrimental effects on tread wear from operating under reduced tire pressure.

Tire Pressure And Temperature

A further study (8) presented the following arguments. A truck tire operating on the highway will increase in pressure by 15 to 20% as the heat in the tire structure is transferred to the contained air over a two-hour period. Tire manufacturers take this into account in selecting inflation pressure; the cold pressure is set so that the hot running pressure will yield the optimised deflection and contact patch. Therefore, preferred running pressure for a truck tire is not the value in the published table but a "hot pressure" that is 15 to 20% higher. For this reason it is important to distinguish between CTI systems that bleed air pressure off (very unusual for North American systems) as it rises with temperature and systems that permits air pressure to build as the tire heat increases. Systems that bleed off tire pressure will run at inflation pressures below the optimum condition. Systems that permit the air pressure to build will run at the optimum

pressure provided the pressure was initially set when the tires were cold. Otherwise they too will not be at the optimum pressure. For this reason Michelin Tire recommends that selected tire pressures be set at approximately 10% above the values published in the data book. Most North American systems set the tire pressure range settings at -2 psi and + 15% of the target pressure. The upper tolerance allows the tire to heat and cool about the target pressure. Therefore the Michelin recommendation appears to be quite conservative.

Note: The above study assumed that the truck tire would be operating at high speeds for extended periods. In practice (18), where variations on vehicle speed result in slower speed operation for part of the trip and short haul time, tires do not approach critical despite travelling at higher than recommended speeds for part of the haul cycle.

The relationship between vehicle speed and tire inflation pressure is critical to tire performance. CTI systems that incorporate a “speed alert” feature that will notify the operator, or override the tire inflation system in the event the design speed for a given pressure setting is exceeded, are considered beneficial. However, for conditions of up to 20% deflation, field tests (18) have shown that tire temperature did not approach critical levels at speeds of 100 km/h for extended periods of operation. Nevertheless the speed alert feature is seen as an important safety feature especially for drivers inexperienced with CTI systems and operation.

The speed with which tire pressure can be adjusted with CTI systems is another important consideration. It is critical that tires receive 80% of the target inflation pressure within 5 minutes of the truck reaching its new operating speed and 100% of the target pressure within 15 minutes. Where handling is a concern, drivers should begin the tire re-inflation cycle at least 5 minutes prior to increasing speed to the new operating condition.

Note: It is now recommended that the SAE guidelines be revised to 70% of cold highway target pressure by 15 minutes and 100% of cold highway pressure by 25 minutes.

Traction Effects

A study conducted by FERIC (9) examined the traction effects of CTI. As the footprint of the tire increases, the traction performance of the tire increases. The relationship between tire inflation pressure, tire sidewall deflection and tire footprint length are shown in table 4. The tire represented in Table 4 is type Toyo M503 - 11R24.5 loaded to 2410 kg. Toyo Tire Canada provided the information.

Table 4. The relationship between tire pressure, foot-print length and sidewall deflection.

Tire Pressure - Footprint length - Deflection				
Tire Pressure	620 kPa (90 psi)	414 kPa (60 psi)	310 kPa (45 psi)	207 kPa (30 psi)
Print Length	25.8 cm	32.0 cm	33.8 cm	36.3 cm
Deflection	8.5%	15%	23%	30%

Traction improvements are dependent on the type of road surface. **Figure 2** shows the tractive capability of a tractor on a loose gravel surface as a function of tire pressure. Axle loads used during the test were as follows; steer axle 5000 kg drive axles 600 kg each. Figure 1 does show the trend in peak tractive force as a function of tire pressure. A separate study (15) found a 34% increase in drawbar pull on sandy roads and 17% increase on clay roads when tire inflation pressures were reduced from 100 to 65 psi.

Braking

Stopping distances for loaded logging trucks was examined at the Nevada Automotive Test Center (10). Stopping distances were reduced on both dry pavement and loose gravel surfaces as tire deflection increased. No appreciable improvement occurred on wet pavement. For dry pavement at 30% deflection (40 psi) stopping distances were 8.6% shorter than with tires at 10% deflection (95 psi). These improvements can only be realised if the wheels do not lock up. When wheels do lock up, stopping distances increase as inflation pressure is reduced (19), therefore the use of ABS brake systems on heavy trucks operating at reduced tire inflation pressure. This argues well for the use of ABS brake systems for vehicles that operate at reduced inflation pressures.

Ride Quality

The drivers of the test vehicles reported a significant reduction in input road vibration to the driver when low-pressure conditions were used. This was particularly noticeable for empty vehicle conditions. The drivers reported a more comfortable ride with less fatigue.

Economics And Environment

In a separate study (13), based on results found by users of a USDA Forest Service road design program, it was determined that the amount of surface material required for low quality forestry roads can be reduced by about 25-50% if CTI is used. This was later proven in field trials (13) and another trial in Lowell, Oregon 1994. In addition, road maintenance costs on such roads can be reduced by about 80%. Improved traction resulting from CTI also allows the tractor to haul heavier loads and reduce cycle times, which improves productivity (5,9,14,19).

Other studies (13, 14, and 21) found substantial savings in road construction and an 84% reduction in the amount of fine silty soil that reached high valued fish streams. It was reported in (13) that a 70% saving in road building and maintenance costs was attributed to the use of CTI. A reduction in road hazard damage to tires was reported as were improvements in ride quality. Shock and vibration through the suspension was reduced by up to 85% under certain conditions.

Potential cost avoidance in forest road construction and maintenance in excess of \$20 million per year was reported in (14). It also reported reduced environmental impacts, lower vehicle operating costs, increased vehicle mobility and driver comfort.

STABILITY AND CONTROL ANALYSIS

General Considerations

To assess the influence of lower tire pressure/higher tire deflection on vehicle stability and control, a 9 axle B-train liquid tank vehicle was chosen as the study. The objective of the task was to determine how lower tire inflation effects vehicle behaviour with respect to the following TAC performance measures.

- Roll stability
- Lateral load transfer
- Friction demand
- Low-speed offtracking
- High-speed offtracking
- High-speed dynamic offtracking
- Rearward amplification

Steady-State Rollover

Heavy trucks can withstand limited lateral acceleration in a curve before rolling over. This rollover limit is expressed in terms of the lateral acceleration, and is given as a proportion of gravitational acceleration (g). Total rollover occurs when all the wheels on one side of the combination vehicle (on the inside of the turn) lift off the road surface. Rollover occurs when the lateral acceleration equals or exceeds the vehicle's rollover limit (which may be assisted by roadway cross-fall or camber). Lateral acceleration on a curve is highly sensitive to speed, and the speed required to produce rollover reduces as the curve radius reduces.

Rearward Amplification

When articulated vehicles undergo rapid steering, the steering effect at the trailer is magnified. This results in increased side force, or lateral acceleration, acting on the rear trailer. This in turn increases the likelihood of the trailer rolling over under some circumstances.

Rearward amplification is defined as the ratio of the lateral acceleration at COG of the rearmost unit to that at the hauling unit in a dynamic manoeuvre of a particular frequency. Rearward amplification (RA) expresses the tendency of the vehicle combination to develop higher lateral accelerations in the rear unit when undergoing avoidance manoeuvres. It is therefore an important consideration, additional to roll stability of the rear unit, in evaluating total dynamic stability; it also expresses the amount of additional road space used by the vehicle combination in an avoidance manoeuvre.

Load Transfer Ratio

Load transfer ratio is defined as the proportion of load on one side of a vehicle unit transferred to the other side of the vehicle in a transient manoeuvre. Where vehicle units are roll-coupled - as in B-doubles - the load transfer ratio is computed for all axles on the vehicle. When the vehicle units are not roll-coupled, as with truck-trailer configurations, they are evaluated as separate units. When the load transfer ratio reaches a value of 1, rollover is about to occur. The LTR is the ultimate measure of rollover stability.

High-Speed Steady-State Offtracking

High-speed offtracking is defined as the extent to which the rearmost tires of the vehicle track outboard of the tires of the hauling unit in a steady-turn at highway speed. High-speed offtracking addresses the road width requirements of the vehicle and can be used to calculate the total swept width of the combination vehicle (that is, the extent to which the lateral excursions of the rear of the vehicle exceed those of the hauling unit in normal operation).

High-Speed Dynamic Offtracking

High-speed dynamic offtracking is a measure of the lateral excursion of the rear of the vehicle with reference to the path taken by the front of the vehicle during a dynamic manoeuvre. This expresses the amount of additional road space used by the vehicle combination in an avoidance manoeuvre.

High-speed dynamic offtracking is computed for the lane-change manoeuvre at a speed of 90 km/h. In each case, the vehicle was made to follow a specific path.

Low-Speed Offtracking

Low-speed offtracking represents a measure of the swept path of the vehicle and its lateral road space requirement when turning at intersections or when turning into loading areas. The offtracking of the vehicle depends on axle position, trailer tongue length and hitch location.

Vehicle Details

Federated Co-operative has been operating a 9 axle B-train under permit in Saskatchewan at a maximum gross weight of 72 tonnes and at a limited maximum speed of 90 km/h. For study purposes, it was assumed that this same unit was loaded to gross vehicle weights of 75,500 kg, 69,000 kg and an empty state of 20,800 kg. The vehicle operating speed was assumed to be up to 100 km/h.

The objective of the study is to determine the sensitivity of general vehicle performance to tire inflation pressure. A vehicle with a higher centre of mass was selected to ensure that sensitivities to dynamic input would be maximised thereby ensuring a conservative analysis of vehicle behaviour. Vehicles of improved design should be expected to fall within the variations of vehicle performance attributed to this vehicle. Under the revised operating procedures, future vehicles will have somewhat better performance attributes than the vehicle examined by this study as these vehicles will be required to pass all of the TAC performance measures.

Some of the key vehicle dimensions are as follows:

- overall length 25.0 m
- lead trailer tank length 9.5 m
- second trailer tank length 10.9 m
- trailer track width 2.6 m

A drawing of the vehicle showing the axle weights used for the three loading conditions is found in [Figure 3](#)).

Test Conditions

The conditions of vehicle loading used were as follows:

- 1) Fully Loaded 75,500 kg
- 2) Partial load 69,000 kg
- 2) Empty 20,800 kg

The tire pressures selected for use in the simulation exercise were changed with axle group, loading condition and vehicle speed, to closely reflect common industrial practice. The tire pressure values used are presented in Table 6.

The cornering stiffness and vertical stiffness data for truck tires, as a function of inflation pressure, were provided to the study by the Goodyear Technical Center in Akron Ohio.

Tire Stiffness

The cornering and vertical stiffness characteristics of tires change as inflation pressure changes. These characteristics have a significant effect on the stability and control of heavy vehicles. Tire cornering and vertical tire stiffness data was obtained from the Goodyear Technical Center. It was non-linearized using the following principle. Using the non-linear cornering stiffness tire data for an 11R22.5 tire at 100 psi inflation pressure, the value of the cornering force at 1 deg.

slip angle was compared to the value of cornering from the linearized data. The ratio was then multiplied by the rest of the values on the non-linear curve to estimate the behaviour at the high slip angles. (note: during simulation the slip angle is not usually above 4 deg.).

Tire vertical stiffness characteristics vary linearly with inflation pressure.

Table 6. Tire pressure settings as a function of loading condition and vehicle speed.

Options	Vehicle Weight (kg)	Operating Speed (km/h)	Tire Pressure psi		
			Steer Axle	Drive Axle	Trailer Axle
a	75,500	100	100	100	100
b	75,500	100	95	85	80
c	75,500	100	80	65	55
d	69,000	100	80	27	55
e	69,000	25	80	27	55
f	Unloaded	100	70	40	35
g	Unloaded	100	70	27	27
h	Unloaded	70	70	27	27

GENERAL FINDINGS

Using the procedures developed in the RTAC Heavy Vehicle Weights and Dimensions study report (16) and other measures, the following vehicle performance attributes were examined using the University of Michigan Transportation Research Institute (UMTRI) Yaw/Roll program:

- roll stability
- load transfer ratio
- rearward amplification
- low speed offtracking
- high-speed steady-state offtracking
- high speed dynamic offtracking

Tables 7-16 contain the results of the assessment of dynamic performance. The vehicle demonstrated good dynamic behaviour. For all cases, with the exception of low speed friction demand, the 9-axle B-train passed the firm TAC performance measures.

**Table 7. Assessment of dynamic performance.
(Option a) GVW 75,500 kg at 100 km/h.
Tire pressures (psi) - Steer (100); Drive (100); Trailer (100).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.351	Good
Load transfer ratio	0.60	0.401	Pass
Rearward amplification	2.00	1.46	Pass
Low speed offtracking	6.00 m	4.33 m	Pass
High speed offtracking	0.46 m	0.314 m	Pass
High speed dynamic offtracking	0.80 m	0.212 m	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

**Table 8. Assessment of dynamic performance.
(Option b) GVW 75,500 kg at 100 km/h.
Tire pressures (psi) - Steer (95); Drive (85); Trailer (80).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.347	Marginal
Load transfer ratio	0.60 (max)	0.422	Pass
Rearward amplification	2.00 (max)	1.48	Pass
Low speed offtracking	6.00 m (max)	4.32 m	Pass
High speed offtracking	0.46 m (max)	0.320 m	Pass
High speed dynamic offtracking	0.80 m (max)	0.214 m	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

**Table 9. Assessment of dynamic performance.
(Option c) GVW 75,500 kg at 100 km/h.
Tire pressures (psi) - Steer (80); Drive (65); Trailer (55).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.341	Marginal
Load transfer ratio	0.60 (max)	0.443	Pass
Rearward amplification	2.00 (max)	1.57	Pass
Low speed offtracking	6.00 m (max)	4.31 m	Pass
High speed offtracking	0.46 m (max)	0.369 m	Pass
High speed dynamic offtracking	0.80 m (max)	0.256 m	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

**Table 10. Assessment of dynamic performance.
(Option d) GVW 69,000 kg at 100 km/h.
Tire pressures (psi) - Steer (80); Drive (27); Trailer (55).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.336	Marginal
Load transfer ratio	0.60 (max)	0.452	Pass
Rearward amplification	2.00 (max)	1.77	Pass
Low speed offtracking	6.00 m (max)	4.29 m	Pass
High speed offtracking	0.46 m (max)	0.418 m	Pass
High speed dynamic offtracking	0.80 m (max)	0.301 m	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

**Table 11. Assessment of dynamic performance.
(Option e) GVW 69,000 kg at 25 km/h.
Tire pressures (psi) - Steer (80); Drive (27); Trailer (55).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.336	Marginal
Load transfer ratio	0.60 (max)	0.020	Pass
Rearward amplification	2.00 (max)	< 1.0	Pass
Low speed offtracking	6.00 m (max)	4.29 m	Pass
High speed offtracking	0.46 m (max)	-	Pass
High speed dynamic offtracking	0.80 m (max)	-	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

**Table 12. Assessment of dynamic performance.
(Option f) Unloaded at 100 km/h.
Tire pressures (psi) - Steer (70); Drive (40); Trailer (35).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.410	Very good
Load transfer ratio	0.60 (max)	0.168	Pass
Rearward amplification	2.00 (max)	< 1.0	Pass
Low speed offtracking	6.00 m (max)	4.48 m	Pass
High speed offtracking	0.46 m (max)	0.140 m	Pass
High speed dynamic offtracking	0.80 m (max)	-	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

**Table 13. Assessment of dynamic performance.
(Option g) Unloaded at 100 km/h.
Tire pressures (psi) - Steer (70); Drive (27); Trailer (27).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.390	Good
Load transfer ratio	0.60 (max)	0.171	Pass
Rearward amplification	2.00 (max)	1.01	Pass
Low speed offtracking	6.00 m (max)	4.45 m	Pass
High speed offtracking	0.46 m (max)	0.177 m	Pass
High speed dynamic offtracking	0.80 m (max)	0.095 m	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

**Table 14. Assessment of dynamic performance.
(Option h) Unloaded at 70 km/h.
Tire pressures (psi) - Steer (70); Drive (27); Trailer (27).**

Performance measures	TAC MOU Value	9-axle B-train	Comment
Net static roll threshold	0.4 g (min)*	0.390	Good
Load transfer ratio	0.60 (max)	0.080	Pass
Rearward amplification	2.00 (max)	< 1.0	Pass
Low speed offtracking	6.00 m (max)	-	Pass
High speed offtracking	0.46 m (max)	-	Pass
High speed dynamic offtracking	0.80 m (max)	0.006 m	Pass

* Recommended value; at times not practical to achieve. TAC MOU - Transportation Association of Canada Memorandum of Understanding

Table 15. Comparison of dynamic performance by option relative to option A (100 psi case).

Performance measures	OPTIONS							
	A		B		C		D	
	V	%	V	%	V	%	V	%
Net static roll threshold	0.35	100	0.35	100	0.34	-3	0.34	-3
Load transfer ratio	0.40	100	0.42	+5	0.44	+10	0.45	+13
Rearward amplification	1.46	100	1.48	+1	1.57	+1	1.77	+21
Low speed offtracking (m)	4.33	100	4.32	-2	4.31	-0.5	4.29	-1
High speed offtracking (m)	0.31	100	0.32	+3	0.37	+19	0.42	+35
High speed dynamic offtracking (m)	0.21	100	0.21	0	0.26	+24	0.30	+43

v - performance values; % - percent change with respect to option A (100 psi).

Table 16. Comparison of dynamic performance by option relative to option A (100 psi case).

Performance measures	OPTIONS							
	E		F		G		H	
	V	%	V	%	V	%	V	%
Net static roll threshold	0.34	-3	0.41	+17	0.39	+11	0.39	+11
Load transfer ratio	0.02	-95	0.17	-58	0.17	-58	0.08	-80
Rearward amplification	<1.0	-	<1.0	-	1.01	-31	<1.0	-
Low speed offtracking	4.29	-1	4.48	+4	4.45	+3	-	-
High speed offtracking	-	-	0.14	-55	0.18	-42	-	-
High speed dynamic offtracking (m)	-	-	-	-	0.10	52	0.01	-95

v - performance values; % - percent of option A (100 psi).

Steady-State Rollover

As tire pressures are reduced, the vertical stiffness of the tires is reduced which decreases the vehicle roll stiffness. However this effect is very small, in the order of 3% for the 75,500 kg vehicle with 20% tire sidewall deflection. All vehicle options exhibited good static rollover threshold characteristics with and without CTI.

Rearward Amplification

The rearward amplification produced by the 9-axle B-train was within the TAC performance criteria for all cases. Rearward amplification increases as tire pressure is reduced. In the case of the 75,500 kg loading condition, RA increased about 8 % with 20% tire sidewall deflection.

Load Transfer Ratio

Load transfer ratio increased about 10% as the tire inflation pressure was reduced to achieve a 20% tire sidewall deflection for the 75,500 kg vehicle condition. Nevertheless, at this reduced tire pressure load transfer ratio was within the TAC guidelines.

High -Speed Steady-State Offtracking

For the 75,500 kg load condition, high-speed offtracking increased by about 18% when the tire pressure was decreased producing a 20% tire sidewall deflection. The increase in high-speed steady-state offtracking remained well within the TAC performance criteria.

High-Speed Dynamic Offtracking

High-speed dynamic offtracking increased by approximately 21% for the 75,500 kg load condition when a 20% tire sidewall deflection was used. Nevertheless, at this reduced tire pressure high-speed dynamic offtracking was within the TAC guidelines.

Low-Speed Offtracking

Lower tire pressures do not significantly effect low speed offtracking.

CONCLUSIONS

Road Costs

The use of variable tire pressures on unsealed and thinly paved roads has proven to be very effective at reducing costs for road, vehicle and tire maintenance. The effects of lower tire pressures on strong roads with thick pavements are less clear. Lower tire pressure has also been found to increase traction and braking capabilities, and to reduce driver fatigue by isolating road vibration particularly on uneven roads.

Vehicle Stability

Heavy vehicle stability and control is significantly effected by tire pressure. The performance measures most effected by tire pressure are high-speed static and dynamic offtracking. This implies that the vehicle will occupy more road space when curving at high speed. This only becomes an issue when vehicle performance exceeds the TAC performance measures. The performance of the 9 axle B-train examined by this study was within the TAC performance measures and is judged to be a sound concept for all tire inflation pressures and load conditions studied.

Operational Considerations

The choice of tire pressure depends on vehicle speed, vertical tire load and road condition. The objective is to select a tire inflation pressure that achieves a certain tire sidewall deflection

(typically ranging from about 15% to 20%). There is no evidence that sidewall deflection in this range negatively effects tire wear, durability or tire recap potential.

When selecting tire inflation pressure values for specific applications, the Tire and Rim Yearbook should be used as a reference or alternatively, the tire manufacturer should be contacted.

It is important that vehicle operators receive training on the proper use of central tire inflation systems. Speed limiting or over-speed warning systems should be required for all central tire inflation systems to prevent vehicle over-speed for a given tire sidewall deflection condition.





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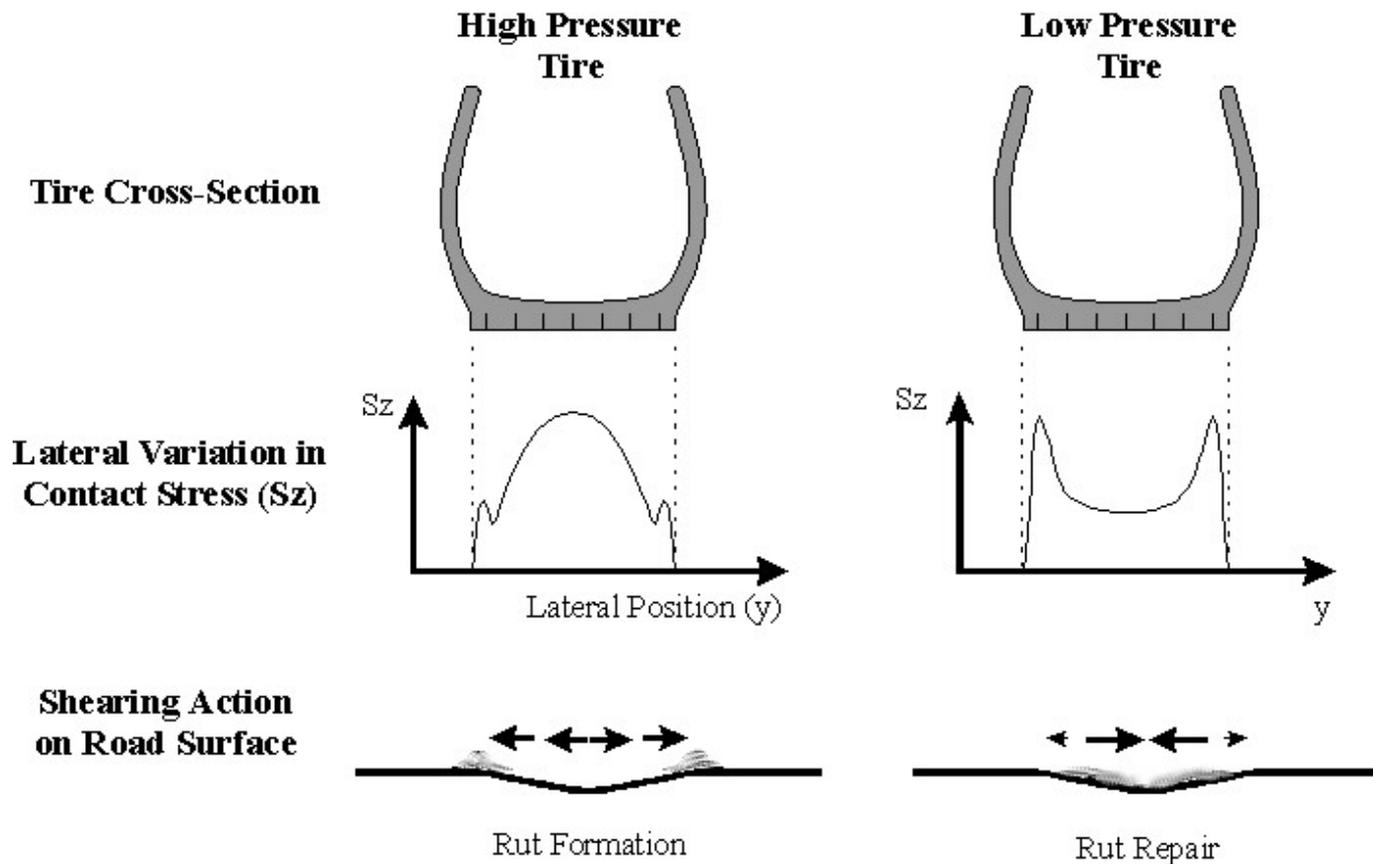


Figure 1. Illustration of contrasting tire force distributions affecting rut formation and repair.

Maximum drawbar pull

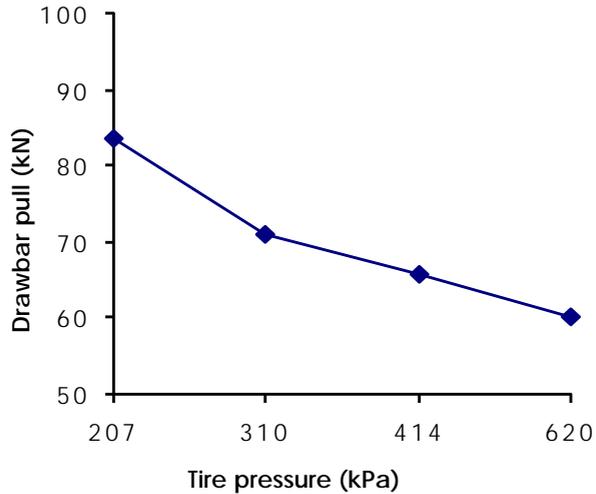


Figure 2. Drawbar pull as a function of inflation pressure.



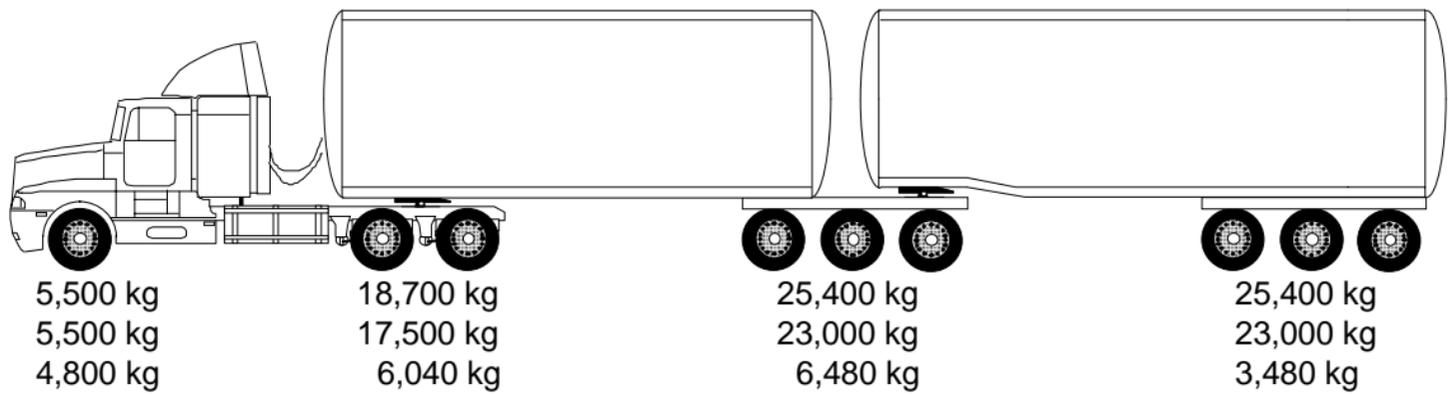


Figure 3. Drawing of vehicle examined (not to scale)

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